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MULTIPLE POINTS OF RUPTURE IN TEXTILE FIBERS; PART I
A PROPOSED MECHANISM

by

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A PROPOSED MECHANISM

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ABSTRACT

Strain-wave propagation is proposed as the mechanism which acoounts for the occurrence of multiple tensile breaks in textile fibers. The breaks are uniformly distributed along the central portion of the test length with a higher concentration existing at or near the boundaries (i.e. the tabs). The region of uniform distribution results from initial random breaks while the high concentrations at the ends are due to reflections of energy waves. Recoverable energy stored in the fiber during extension is the driving force for wave propagation. The dependence of multiple breaks on testing length, rate of extension, temperature, medium, morphology, and tenacity at break is discussed.

INTRODUCTION

When secondary acetate or triacetate fibers are extended to rupture on a constant rate-of-extension tensile tester, as many as 90% of the fibers tested may break at more than one point. There may be two, three, or, in rare cases, four points of rupture along the fiber axis. The broken pieces not attached to the boundaries (tabs or jaws) are thrown out of the test section to distances up to 8 in.

Little or no discussion of such phenomena has appeared in the literature, although Lyons and Prettyman mentioned occasional multiple breaks in the use of the ballistic pendulum for impact testing of tirecord [5]. A preliminary study of materials which exhibit multiple breaks has therefore been undertaken. The experimental results are presented in this article, along with a proposed mechanism by which these breaks occur. Discussion of the possible reasons why multiple breaks occur in certain types of fibers,and not in others, is intended for a subsequent publication.

Strain-Wave Propagation

The occurrence of multiple breaks can be logically explained by a hypothesis of strain-wave propagation. First consider the initial break. It is reasonable to believe that the ultimate weakest point in a specimen should be located in a random manner, independent of subsequent events which culminate in multiple breaks. This initial fracture has received much theoretical study; it has been described as a combination of an over-all yielding of the fiber structure (plastic deformation) along with the propagation of a crack in a catastrophic manner at a point of stress concentration, leading to a localized breakdown of the submicroscopic structure. Energy is put into the fiber during extension, and the greater fraction is used irreversibly through internal friction to increase thermal oscillations in the polymer chain segments. Some portion of the input energy, however, is not dissipated but is stored reversibly by elastic structural distortions. This energy is recoverable as useful mechanical work upon release of stress.

Now consider the process accompanying the release of strain in the broken stubs. The drop in stress at the initial breaking point is instantaneous, so that strain is not relieved quasistatically. Rather, a wave of strain relaxation travels toward the fixed ends in each of the two fiber stubs in the form of compressional displacements of the chain segments. Upon reflection at the fixed boundary, the total recoverable energy in the fiber stub, less that dissipated by internal friction in transit of the wave, is available to produce further rupture of the fiber structure. It is postulated that, discounting dissipation, the longer the stub, the greater would be the energy at reflection. Experimental results indicate, however, that dissipation is an important part of the process.

Prior to the initial break, ductility serves to round the apex of all flaws, thereby reducing stress concentrations and permitting greater elongation. After the initial break, the forces produced by energy contained in the wave pulse are applied on such a short time scale that energy can no longer be dissipated by localized flow, and stress concentrations are less easily relieved. Considering also that wave reflection results in high concentrations of stress near the fixed boundaries, further fractures in appropriately susceptible materials under favorable conditions would not be totally unexpected.

A mathematical description of the wave propagation would be extremely difficult, if not prohibitive, considering the present state of development of the theory of wave propagation in inelastic media in which the stress-strain relation is not linear. The wave propagation hypothesis as the cause of multiple breaks is supported, however, at least qualitatively, by literature reporting classical wave propagation experiments.

Impact testing where loading is at, or approaches, sonic rates is a similar, although not entirely analagous process. Among the earliest experimental work (1972) on fractures produced by stress waves was that carried out by J. Hopkinson who measured the strength of steel wires when they were suddenly stretched by a falling weight. It was found that the wires generally broke near the top end upon reflection of a stress wave [4].

In tests described by Smith, et al [10] and Stone, et al [11], one end of a fiber was fastened to a head mass which was impacted; the other end to a tail mass. Smith et al stated increases in local strain always occur first upon reflection at either the head or the tail. Increases in the local strain at an intervening point occur later, but these strains never exceed the head or tail strains in magnitude. For this reason, it is to be expected that a uniformly strong filament will break only at the ends. [11].

The process which occurs after the initial break in a quasi-static application of tension is then somewhat analogous to that occurring before the initial break in impact testing. The boundary conditions for wave propagation differ somewhat in that there are two fixed boundaries in the impact test, while after the initial break in quasistatic loading, there is one fixed boundary and one free boundary. In the impact test, the fiber is always in tension at the boundaries, and a wave pulse is reflected unchanged. In the case of the quasistatic process, the shape of the reflected pulse is the same but is opposite in sign; a compression pulse is therefore reflected as a similar pulse of tension. Certain phenomena, however, would be expected to be characteristic of both systems. For instance, a preponderance of boundary breaks would be expected if the proposed strain-wave mechanism for multiple breaks is correct.

Results and Discussion

All tensile testing was performed on single filaments mounted with epoxy glue on plastic tabs. Unless otherwise stated, atmospheric conditions were standard (70°F, 65% R. H.), and the rate of extension was 50% per min. Frequencies of multiple breaks were determined from tests on as many as 100 fibers of a given type, and in no instance less than 20.

Breaking Positions

As a first approach to the study of multiple break phenomena, data indicating the points along the fiber axis where rupture occurred were collected. A large piece of black cardboard was placed beneath the lower tab to catch freed central sections thrown out at break. At the outset of each test a barely discernible amount of red coloring was applied at a distance of about 1/4 the fiber length away from the upper tab. If triple breaks occurred (2 central sections), the section whose original position was nearer the upper tab could be identified by the red spot. Measurement of the lengths of the central sections and the pieces remaining on the tabs allowed determination of the positions of all rupture points. A diagram of breaking positions could then be constructed, arbitrarily correcting for extension at break.

The breaking positions found in testing 50 3-inch acetate fibers are shown in Figure 1. The length, after correcting for extension, has been divided into 10 linearly equal cells plus two arbitrary boundary regions at the tabs, and the breaks recorded according to locations within these 12 cells. In this case, a boundary break is considered to be any break occurring within 1/8 in. of a boundary. The method of establishing the boundary region is discussed in the Appendix.

It can be seen that 121 rupture points were counted for these 50 acetate fibers. A very high proportion of the rupture points (70) were at the boundaries (i.e. at or very close to the tabs to which the ends of the fibers were connected). A Chi-Square test indicates that non-boundary breaks occurred at random points along the fiber axis. The types of breaks are shown in Table I.

For a material which exhibits only single breaks, the breaking positions should also be randomly located. The breaking positions for 85 viscose rayon fibers are shown in Figure 2. No multiple breaks occurred. The distribution is uniform, as would be expected assuming no preferred breaking positions.

The experimental distribution of acetate breaking positions can now be reconciled with the proposed wave-propagation hypothesis; i.e., the uniform distribution of breaking positions along the fiber axis is representative of initial random breaks while the high concentration of boundary breaks is indicative of breaks due to the reflection of energy waves at the boundaries.

Microscopic Examination

Microscopic examination of broken acetate fibers at magnifications of 460 X revealed that all breaks, single or multiple, were sharp, as if cut by a razor blade. No cracks, surface or internal, were visible. Transverse fissures similar to those observed by Prevorsek and Lyons [7] in fatigued fibers under oblique lighting were not evident.

Effect of Testing Variables

Testing Length

The dependence of multiple breaks on testing length is shown in Figure 3. The linear portion of the curve for short testing lengths is a consequence of the fact that the energy stored during extension increases in proportion to testing length. The decrease in slope of the curve for lengths longer than 3 in. may be indicative of an attenuation effect. In viscoelastic materials internal friction rapidly dissipates the energy sustaining wave propagation. If the fiber stub is long enough, there may be insufficient energy remaining in the wave upon reflection at a boundary to rupture the material at the apex of a crack.

A high attenuation effect would also seem to indicate that the probability of rupture occurring at any reflection of the wave other than the first would be low. Very few fibers would then be expected to sustain more than three breaks.

The lack of consideration given multiple breaks in the literature may be a result of the A.S.T.M. standard which specifies testing lengths longer than 4 in. [1]. It may also be due to the infrequent occurrence of multiple breaks at normal testing conditions, except in the case of the acetates.

Rate of Extension

From the data in Table II, it is inferred that the occurrence of multiple breaks is independent of rate of extension[1]. Therefore, processes which occur in the fiber following the initial break are dependent for the most part only upon the state of the fiber structure at the time of the initial break. This result supports the proposed wave mechanism which is based upon events occurring in the fiber after loading has ceased.

Effect of Variations in Fiber Structure

Temperature and Medium The data in Table III indicate that by changing the temperature and/or medium in which fibers are broken, it is possible to eliminate multiple breaks in acetate and induce them in rayon.

The apparatus used for low-temperature tensile testing is described elsewhere [8]. The fiber is immersed in heptane in the inner tube of a dewar vessel. In the outer chamber, a cryogenic mixture of solid carbon dioxide in isopropyl alcohol produces a temperature of $-76^{\circ}C$ at atmospheric pressure. The use of heptane as a cooling agent is merely a convenience and does not significantly affect the tensile properties or the number of multiple breaks.

The effect of a decrease in temperature is to reduce plastic deformation, necessitating less strain for embrittlement. In contrast, at $90^{\circ}C$, secondary acetate is above its glass transition temperature ($69^{\circ}C$), and rupture is essentially a process of plastic

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[1] This conclusion is not necessarily applicable to high-speed testing, a condition not included in the present experimental program.

deformation and viscous flow (ductile fracture). Solvation with water of functional groups which participate in secondary bonding also allows molecular flow processes to occur more readily. In the case of the cellulosic structure, intermolecular attractive forces are of the hydrogen-bond type. These polar bonds (capable of solvation with water) are responsible for preventing chain slippage in the dry fibers.

The results indicate that, in general, multiple breaks decrease with increasing plastic deformation. Apparently, the greater internal friction increases ductile energy dissipation, thereby reducing the amount of energy which can be stored for useful work and expended upon release of stress at the initial break.

Chemical Treatment By varying the degree of crystallinity and/or orientation of secondary acetate or triacetate, the propensity for multiple breaks can be significantly altered. In one experiment, a slight degradation of the secondary acetate structure was caused by treatment with a dioxane-water solution. When the washed and dried fibers were tested, only 25% multiple breaks were obtained as opposed to 80% in the untreated material. Characteristic tenacity-extension curves for the treated and untreated samples are shown in Figure 4.

It is apparent that the occurrence of multiple breaks is closely related to the internal fiber structure as established by the condition of the test.

Multiple Breaks in Fibers Other than Secondary Acetate

Triacetate was found to behave in a manner similar to that of secondary acetate at all conditions. However, these were the only materials exhibiting multiple breaks at standard conditions. Viscose rayon exhibited no multiple breaks at standard conditions but as many as 70% at -76°C. The following materials exhibited no multiple breaks at standard conditions or at -76°C: nylon 66, Dacron[2], Fortisan[3], Vicara[4], and a coarse, crimpless wool.

To the extent of the experimental work performed by the authors, multiple breaks have been observed only in materials of cellulosic structure.

Distribution of Breaking Strengths - Secondary Acetate

A breaking force vs. frequency plot for 100 secondary acetate fibers is shown in Figure 5. The total distribution is bimodal, composed predominately of a distribution of high-tenacity multiple breaks and a distribution of low-tenacity single breaks. The fact that the skewness to the right is opposite that predicted by the weak-link theory is an interesting, but not particularly important, point in the present discussion.

The bimodal distribution indicates that the structure of

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[2] Registered trademark of E.I. duPont de Nemours & Co.,Inc.

[3] " " of Celanese Corp. of America

[4] " " of Virginia-Carolina Chem. Co.

acetate at rupture may be such that the initial break is affected by more than a single fracture mechanism. Bimodal tenacity distributions have been reported by Moseley in nylon 66 [6] and by Cheung in viscose rayon [3]. Bimodal distributions in fatigue lifetime have been reported by Prevorsek and Whitwell in polyacrylics [9] and by Barella in cotton yarns [2].

The concentration of multiple breaks at high breaking loads in Figure 5 is a consequence of the fact that for any one material, those specimens of greater tenacity are capable of storing more energy, other things being equal. In general, if two rupture mechanisms exist for the initial break, multiple breaks would be expected to be associated with higher strength.

From the hypothesis of strain-wave propagation, it would be concluded that if two materials of different strength store the same amount of eneryg, the material of weaker structure would be more likely to exhibit multiple breaks. In terms of quantitative tensile properties, tenacity as well as stored energy must be used to predict whether nylon, for example, would be more susceptible to multiple breaks than acetate. Since their breaking tenacities differ by a factor of five, there is for a given amount of stored energy a greater probability in acetate than in nylon.

In summary, breaking tenacity is a counterbalancing factor. More energy may, in general, be stored in high tenacity fibers, but the probability that this energy can cause additional fracture is decreased by the increased breaking tenacity.

Conclusions

Any proposed hypothesis for the mechanism producing multiple breaks in single filaments must account for the preponderance of boundary breaks which occur in all cases where multiple breaks have been observed. The inordinately large number of multiple breaks in 3-in. acetate at standard conditions precludes explanations based upon either multiple weak links of identical strength or multiple fracture zones, also with identical characteristics.

The proposed mechanism of strain-wave propagation sustained by recoverable energy stored in the fiber during extension is consistent with the preponderance of boundary breaks, the dependence on testing length, and the independence of rate of loading.

Continuing work at Textile Research Institute is concerned with the estimation of the recoverable energy for various types of fibers and its relation to the tenacity. Theories concerning reasons for the existence of multiple breaks in some fibers and not others are currently based upon this concept.

Appendix

Establishment of the Boundary Region

If multiple breaks occur due to wave propagation, the breaks at the boundaries cannot be interpreted in the same manner as ordinary boundary breaks, commonly known as tab breaks. The boundary region is determined by choosing a length of fiber, such as 1/8 in., adjacent to a boundary, and provisionally considering this length as unduly under the influence of the boundary. The remaining fiber length is divided into 10 equal cells and the breaking position diagram is constructed. The minimum length which best best randomizes the numbers in the cells is selected as the optimum. A Chi-Square test is used as the criterion of randomness. It can be seen that if the boundary length of fiber is too short, the fiber end cells would be overfilled.

This method of establishing the boundary region is not limited to materials where multiple breaks occur; it is recommended for all work in which interest exists in the domain of influence of a boundary.

Acknowledgment

Fiber samples for this project were obtained from Celanese Corporation of America, Chemstrand Research Center, Inc., and E. I. duPont de Nemours and Company.

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TABLE I. Frequency of Multiple Rupture Points; Secondary Acetate; 50 den., 3 in.

Type of Break		Frequency
Number Per Fiber	Number at Tabs	
1	0	3
1	1	2
2	0	1
2	1	18
2	2	2
3	1	4
3	2	18
4	2	2
		50

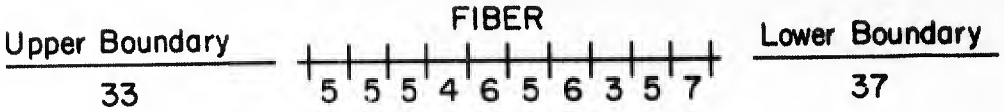
TABLE II. Dependence of Multiple Breaks on Rate of Extension

Rate of Extension %/min.	Multiple Breaks (%)
5	90
50	85
500	90

TABLE III. Multiple Breaks (%) in Acetate, 50 den. and Rayon, 15 den*.

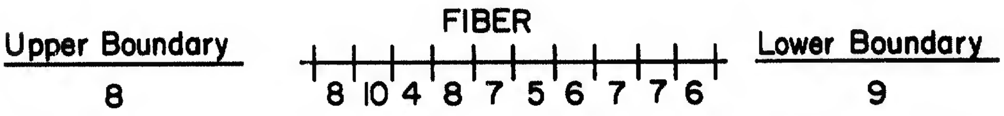
	Dry		Wet	
	21°C	-76°C	21°C	90°C
Secondary acetate	85	90	30	0
Viscose rayon	0	50	0	-

* All test lengths were 1 in. except for secondary acetate at 90°C for which length was 3 in.



$$\chi^2(\nu=9) = 2.13$$
$$\chi^2(0.95, \nu = 9) = 3.33$$
$$\chi^2(0.05, \nu = 9) = 16.92$$

Fig. 1. Breaking positions for secondary acetate, 50 den., 3 in.



$$\chi^2(\nu=11) = 4.37$$
$$\chi^2(0.95, \nu=11) = 4.57$$
$$\chi^2(0.05, \nu=11) = 19.68$$

Fig. 2. Breaking positions for viscose rayon, 3.75 den., 1 in.

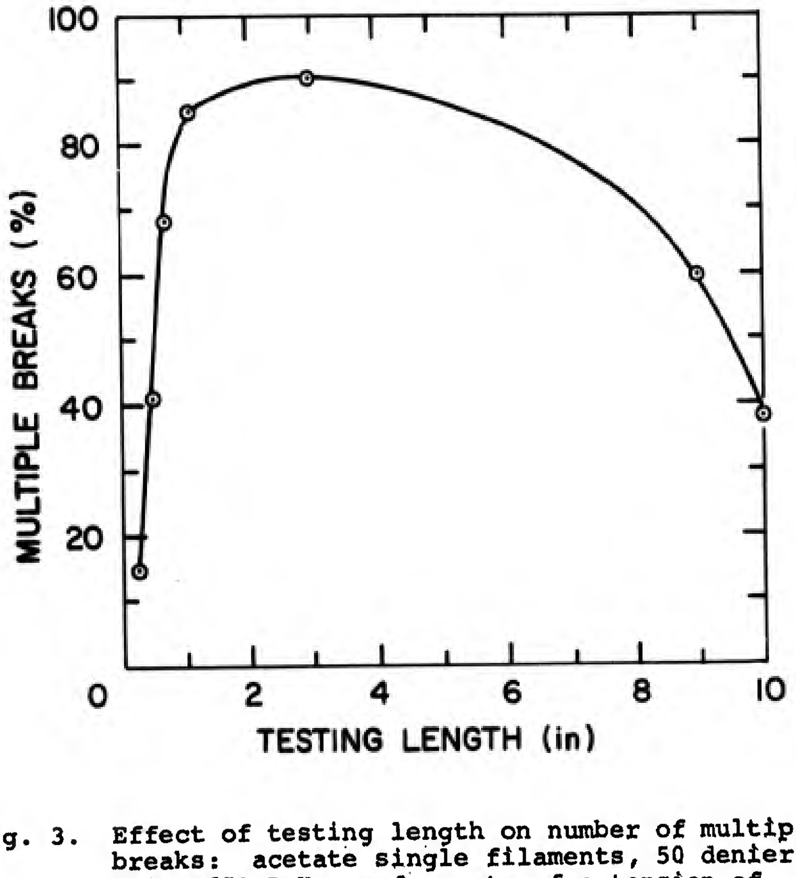


Fig. 3. Effect of testing length on number of multiple breaks: acetate single filaments, 50 denier, 21°C, 65% R.H., and a rate of extension of 50%/min.

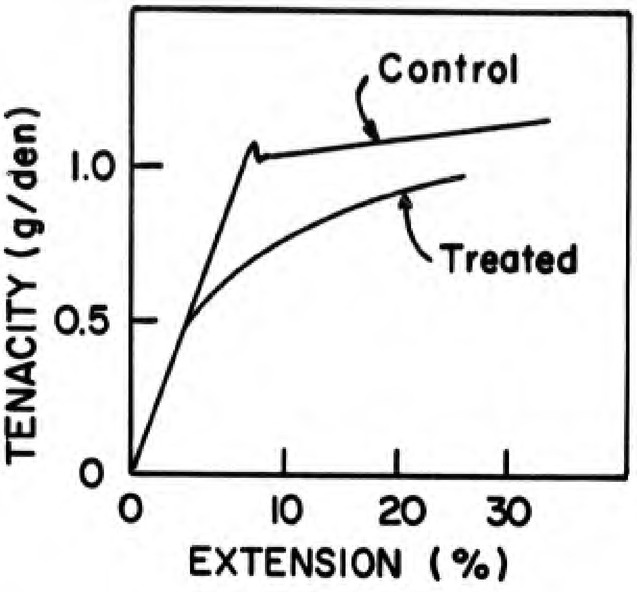


Fig. 4. Effect of dioxane treatment on secondary acetate.

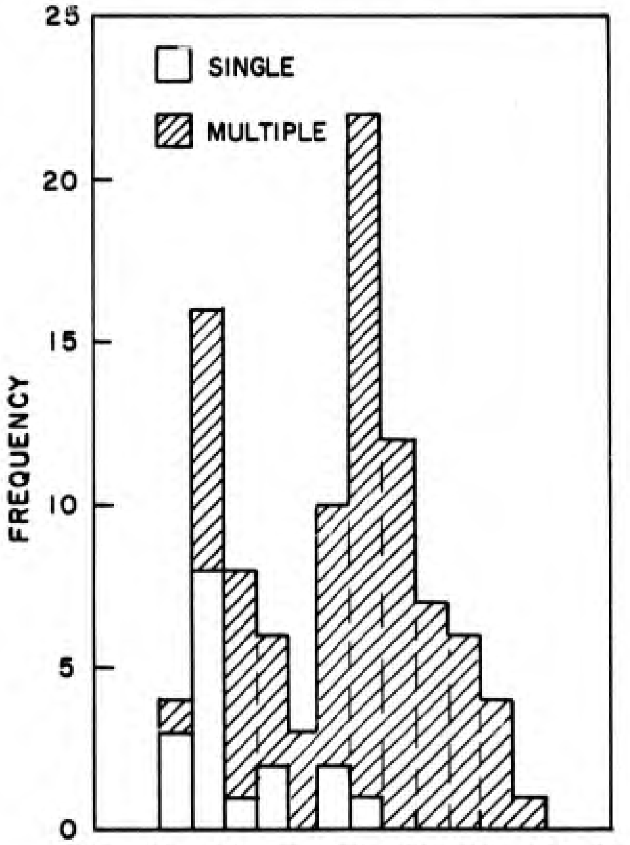


Fig. 5. Breaking force frequency plot, secondary acetate 50 den., 1 in.

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13. ABSTRACT

Strain-wave propagation is proposed as the mechanism which accounts for the occurrence of multiple tensile breaks in textile fibers. The breaks are uniformly distributed along the central portion of the test length with a higher concentration existing at or near the boundaries (i.e. the tabs). The region of uniform distribution results from initial random breaks while the high concentrations at the ends are due to reflections of energy waves. Recoverable energy stored in the fiber during extension is the driving force for wave propagation. The dependence of multiple breaks on testing length, rate of extension, temperature, medium, morphology, and tenacity at break is discussed.

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